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Remote Sensing and Problems of the Hydrosphere

A Focus for Future Research

Proceedings of a working group meeting
held at New Orleans, Louisiana
May 9-11, 1979

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Remote Sensing and Problems of the Hydrosphere

A Focus for Future Research

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Scripps Institution of Oceanography
La Jolla, California

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PREFACE

Water quality problems per se are extraordinarily complex and are further complicated by the myriad of unresolved fundamental issues facing marine scientists today. Amongst others, complexities arise from characteristic differences in chemical reactions in which various pollutants are involved, the lack of a thorough understanding of the interaction of each with the environment, and the multitude of pathways that pollutants follow in nature. Complicating this already complex set of problems are those additional unresolved factors relating to chemical, biological, geological, and physical dynamics of natural ecosystems. When these factors are combined, the resulting water quality problems scientifically appear to be all but intractable. To overcome this difficulty, we must continue to break these problems down into their fundamental components, addressing each aspect from a scientifically sound basis.

The NASA research endeavor primarily follows this tried and proven fundamental approach to research. Although some of our work has used a site-specific empirical approach, this has served to underscore the complex nature of the problem. In the future NASA will continue to focus its research on the underlying problems of water quality which are addressable with space technology. To this end, this report and the companion report, Remote Sensing and Problems of the Hydrosphere - NASA Conference Publication 2109, outline the extent of water quality research problems and serve as a valuable measure for assessing the focus of our ongoing research efforts.

The National Aeronautics and Space Administration acknowledges the efforts of Dr. Edward Goldberg and the other scientists who participated in this study and expresses to them its sincere appreciation.

W. Stanley Wilson
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I. OVERVIEW

Edward D. Goldberg

The program herein presented reflects a double distillation of concepts and ideas. The first processing took place in January 1979 at Warner Springs, where 40 scientists and engineers assembled to ascertain what first order problems in water quality might be amenable to solution through remote sensing techniques. The scientists in general were unaware of the capabilities of NASA equipment; the engineers had not considered the priority concerns of Earth scientists. The proceedings of this workshop are published as Remote Sensing and Problems of the Hydrosphere, NASA Conference Publication 2109.

A second gathering of a dozen scientists (see appendix) took place in New Orleans in the spring of 1979 to assess the Warner Springs findings and to more sharply focus upon what may be the most important problems whose solutions are possible. Four research areas were defined and the problems associated with them discussed:

BIOPROCESSES

1. Eutrophication through man's activities
2. The role of fronts in biological phenomena in the oceans

GLOBAL GEOCHEMICAL PROBLEMS

1. The carbon dioxide increase through man's activities and its impact on climate
2. The measurement of heavy metal fluxes from the Earth's surface (land and water) to the atmosphere

GAS AND AEROSOL FLUXES

1. The fluxes of trace gases
2. Sea-salt aerosol production
3. The effect of sea surface microlayer on gas and aerosol fluxes

COASTAL SEDIMENTATION

1. Coastal fine particle sediment systems
 2. Episodic events and coastal sediment systems
 3. Routes and rates of sediment transport on continental shelves
 4. Dredging and dredged material disposal
- 1

Perhaps surprising is the ready identification of a small number of high priority problems, most of which reflect some phase of man's manipulation of his environment. The participants in both conferences came from a variety of pursuits in the academe, industry, and government. Yet their pressing concerns were rapidly translated into a relatively small number of well-defined problems. There was immediate recognition that remote sensing provided far greater coverage in time and space for measurement of physical and chemical parameters than do conventional fixed stations or ships.

There are several commonalities running through most of the problems. First of all is the difficult but urgent need to measure fluxes of materials into and out of aqueous systems, i.e., the entry of time into the experiment.

Secondly, there is an urgent need to improve our measurement techniques, be they of carbonates in seawater, fluorinated hydrocarbons in the atmosphere, or the suspended load in rivers. At the Warner Springs Meeting the assembled scientists were pleasantly surprised by the measurements now possible from remote sensing devices and by the optimism shown by the engineers with respect to the tractability of the measurement problems posed to them.

Clearly, all of the problems formulated herein will not be solved in the near future. Also, there are other problems of equal importance that have been overlooked by the assembled investigators, most probably as a consequence of the limited number of participants. Still, we do have a springboard for future work.

This document consists of sections contributed by the individual participants with a minimum of editing for publication.

II. BIOPROCESSES

Dominic M. DiToro, Richard L. Iverson,
and James J. McCarthy

A. Introduction

Remote sensing of the hydrosphere is a technical discipline which has developed to a point where it can now contribute to the solution of important scientific and environmental problems. There is neither a lack of problems nor a lack of measurement requirements and possible applications of present or projected remote sensing capability. This is particularly true in physical, chemical, and biological investigations of large water bodies which are invariably limited by lack of data. In choosing our recommendations of first-order problems to which remote sensing should be applied we have been guided by the following criteria:

- (a) The importance of the problem as indicated by present level of scientific and engineering effort being expended in improving our understanding of its causes and of developing methods for controlling its consequences
- (b) The unique capability of remote sensing to provide synoptic large spatial scale and short temporal scale data as compared to conventional ship-based sampling procedures
- (c) The parameters available for measurement using present and projected remote sensing techniques
- (d) The demonstrated need for these measurements in ongoing and planned investigations.

We recommend two classes of problems be considered which are related in certain respects but distinct in emphasis: (1) eutrophication and (2) location and characterization of fronts.

B. Eutrophication

1. Statement of the Problem

(a) Why It Is Important Scientifically and Politically

Artificially accelerated eutrophication in natural waters is a manifestation of man's age-old practice of disposing of his wastes in the most convenient river, lake, or ocean. This process, which is often referred to as cultural eutrophication, can result from the perturbation of the environment which (1) stimulates the production of algae without a concomitant increase in cropping or other loss processes, (2) stimulates certain nuisance algae to out-compete other more desirable algae, or (3) suppresses natural grazing processes. The result of extreme cultural eutrophication is an accumulation of algae which

are classed as undesirable because they result in a disruption of the normal food web. The herbivores do not accept them as suitable food substitutes for the algae which have been displaced, and with advanced eutrophication the water body usually loses important finfish and shell fish populations. The resultant accumulation of algae depletes nutrients from the water, the algae become light limited, and subsequently decompose. The decaying algae are an aesthetic problem on beaches, they affect the taste and odor qualities of the water supply, and when in high populations, the bacterially mediated decomposition can result in reduced oxygen concentrations and widespread fish mortality.

Cases of cultural eutrophication have been thoroughly documented for polluted natural waters, and corrective measures have successfully reversed the development of eutrophication in some instances, primarily small freshwater lakes. However, the remedial measures for the eutrophication of large water bodies are extremely costly and the projected degree of their effectiveness is still a matter of debate. It is these problems that are currently of major importance.

The first biological indication of cultural eutrophication is a change in either biomass or the species composition of the algae, the organisms at the base of the aquatic food web. Oceanographers and limnologists are often unable to recognize such changes in the biota until they have reached fairly dramatic levels. Consequently the scientist usually becomes aware of a developed eutropic condition or a large population bloom (such as red tides or the unusual dinoflagellate dominance and dissolved oxygen depletion in the New York Bight during the summer of 1976) after it has developed. At the heart of this problem is our inability to synoptically monitor large areas for quantity and quality of algal biomass.

(b) Consumers of Results

Information regarding eutrophication in both marine and fresh waters is of great use to scientists interested in factors which regulate both biological productivity and community structure. Surveillance of the Great Lakes is currently being carried out by a joint U.S.-Canadian effort and large-scale control programs are being designed. Investigations of coastal water eutrophication in the New York Bight by the MESA program of NOAA and in the Chesapeake Bay by EPA are currently underway. NASA remote sensing data can complement these efforts and add significantly to the available data. This information is needed in order to make decisions regarding the management of pollutant inputs, fishery resources, and recreational uses of the natural waters. Academic scientists who are interested in understanding the process of eutrophication would also be major users of these large data sets of environmental parameters which influence productivity.

2. What Needs To Be Measured?

(a) Limitation of Existing Conventional Techniques

The parameters which must be measured are the amount of biomass in the water column, its species composition, its rate of production, numerous environmental factors which regulate productivity (light, temperature, salinity, and

nutrients), and, most importantly, the time and space scales of the variability in these features. All of the above can be measured from stationary ships, and in most instances the analytical precision is adequate.

The major limitations to conventional approaches are: (1) the measurements are not all available in real time, (2) even with multiple ship operations, the restricted spatial coverage limits the ability to generalize about the overall study area, and (3) no information is available on the behavior of the study area during the intervals between sampling periods. The scales of time which are important in eutrophication can be as small as days since the organisms replicate in periods of this length. But of equal importance is the longer term view which may range from a few to several years. Spatial scales of importance range from a few to hundreds of kilometers. The observations made from shipboard actually characterize only a small volume of water, and whereas we know that we can generalize from such observations to areas of hundreds of square kilometers in the open ocean, we are limited to areas of single kilometers or less in physically dynamic coastal regions of oceans and large lakes. Large-scale variability, even in the open waters of the Great Lakes, has also been observed during intensive lake-wide sampling (e.g., during the International Field Year investigations of Lake Ontario). To a large degree, the present limitations stem from the need for spending a large part of the day on station in order to properly characterize the properties mentioned above and the transit time between stations.

(b) Feasibility and Capability of Remote Sensing Techniques

Remotely sensed synoptic sea surface temperature, light penetration, surface currents, and quantity and quality of plant pigments at a daily frequency for study areas of interest would yield the data which, when combined with shipboard measurements of the other parameters of importance, would greatly improve the understanding of this problem which is otherwise difficult. We are now at the point where the development and verification of sound models for eutrophication are essential if we are to progress, and remote sensing is a key component in such an endeavor in large lakes and coastal waters.

3. Recommendations

Of prime importance in a NASA effort to apply remote sensing to the problem of eutrophication is a solid interfacing with other governmental agencies which are conducting scientific field programs which address this problem. Such interagency limnological and oceanographic investigations would provide the proper focus in addition to the shipboard observational and experimental capabilities. They must also have a strong modeling component which would greatly benefit from synoptic data which remote sensing can generate.

NASA should also support efforts to improve knowledge of optical physics in order to further develop the potential of both active and passive sensing systems. A program to assess the degree to which existing technology can provide accurate estimates of the depth of light penetration, the quantity and quality of plant pigments in waters of different depths, and in waters with different amounts of nonplant particulate material, and other variables is required.

C. Location and Characterization of Fronts

1. Statement of the Problem

(a) Why It Is Important Scientifically and Politically

Fronts are features characterized by sharp gradients in physical and biochemical variables in aquatic environments. The length scales of fronts range from 10^2 meters for some estuarine plume fronts to 10^6 meters for some continental shelf fronts. Fronts persist on the order of hours for some tidal fronts to years for the shelf break front in the Bering Sea. Factors which interact to cause frontogenesis are not well understood; therefore frontogenesis is currently an active research area in physical oceanography. Salinity gradients associated with shelf break fronts suggest that a balance between freshwater input from rivers along the northeast coast of North America and in the Bering Sea and offshore oceanic water is important in frontogenesis. The tides are known to be a primary source of energy for frontogenesis in shelf waters around the British Islands. The M2 internal tide has been strongly implicated in frontogenesis of the Nova Scotian shelf break front. All of the evidence to date suggests that fronts may be an important site for energy dissipation on continental shelves. Research in localized, readily available sites where regular physical dynamics occur is very important in attempts to understand the dynamics of the upper ocean.

Major fisheries along the east coast of the North American continent and in the Bering Sea are associated with continental shelf fronts. Enhanced dynamics of phytoplankton and zooplankton have been reported in fronts relative to dynamics in shelf waters not influenced by fronts. Distinct pelagic and benthic food webs appear to be associated with different regions along a cross-shelf transect through several fronts in the Bering Sea shelf waters. These food webs are coupled to the fronts which are stable features throughout the spring and summer. The fronts afford specific sites in which to investigate dynamics of significantly different food webs. Factors which control nutrient input to the photic zone in fronts are poorly understood, although the M2 internal tide may drive vertical advection of water in the Scotian shelf break front.

The political significance of fronts is coupled with the tremendous biological productivity of fronts. Foreign fishing vessels are currently the primary vessels working fronts along the continental shelves of the United States. Management of U.S. coastal fisheries along the Atlantic coast and in the Bering Sea will be primarily focused on fronts in the near future.

(b) Consumers of Results

There are a number of investigations of frontal processes which would benefit now or in the next several years from application of NASA technology to location and characterization of mesoscale features of fronts. Some of these investigations include PROBES, a study of the Bering Sea funded by NSF Polar Sciences, DOE-funded investigations of the Gulf Stream front along the southeast Atlantic shelf, NMFS investigations of fronts near Georges Banks, and various smaller projects funded by NSF which are addressing front processes in the

New York Bight. NASA technology could be used to assist NMFS in monitoring the activity of fishing vessels in fronts along the continental shelves of the United States.

2. What Needs To Be Measured

(a) Limitations of Existing Conventional Techniques

Ships are the primary platforms which have been used in research on fronts, although some visible spectrum photography from light aircraft and satellites has been used to show spatial scales of fronts. Ships are obviously limited in the distance over which samples can be taken in short periods of time. This creates serious problems both in characterizing the spatial scales of large fronts and in obtaining even quasi-synoptic data sets. Large-scale motion associated with fronts is not very well known primarily as a consequence of limitations in shipboard data collection. Shelf break fronts appear to oscillate with the tides. Large-scale waves have been observed in shelf break fronts along the northeastern U.S. coast. Events of time scale 2 to 4 days appear to be important in frontolysis near canyons along the southeastern U.S. Atlantic coast. The temporal response of fronts to transient forcing events such as wind stress is largely unknown because ship scheduling is not responsive to the need to study transient events.

(b) Feasibility and Capability of Remote Sensing Techniques

Remote sensing of surface temperature, salinity, color, reflectance, and roughness would provide a set of data from which to obtain estimates of the spatial scales and near-surface dynamical features of fronts on all scales. The spatial resolution required for different variables depends on the nature of the front under investigation. For example, a resolution of 100 m would be adequate for characterizing the fronts in the Bering Sea or along the Atlantic coast of North America. Finer levels of resolution would be required for the study of plume fronts associated with the Mississippi or Columbia Rivers. The laser methods for measuring turbidity and chlorophyll now under development by NASA would allow finer resolution of features within fronts. Laser data would presumably be available more rapidly than would data collected by satellite, a consideration which is important when remote and surface data collection for real-time experiments is planned.

3. Recommendations

(1) NASA personnel should interact with investigators actively involved in frontal research so that information about front characteristics, data requirements, and actual and potential instrument capability can be exchanged in a timely manner.

(2) NASA should allocate resources to examine Coastal Zone Color Scanner (CZCS) data for evidence of fronts in locations where their existence is suspected based either on empirical or theoretical bases. This effort would determine the length scales of biologically active fronts on continental shelves

where large gradients in chlorophyll occur. Time series observations should be conducted for selected fronts to characterize the seasonal pattern of changes in frontal chlorophyll signature.

(3) NASA should interact with programs which are now addressing frontogenesis so that ground truth can be coupled with CZCS imagery in an attempt to elucidate forcing variable frequency and frontal response between periods when ships are on station. The input of NASA will be critical in attempts to understand the time scales of frontogenesis and frontolysis.

(4) NASA should continue the development of laser remote sensing instruments. Development should proceed in concert with field tests of the instruments in locations where frontal research is being performed. This would allow feedback between instrument development and application so that the laser methods are optimized for the variables of interest. When instrument reliability and performance are satisfactory, the instruments should be programmed into ongoing and planned research on fronts.

III. GLOBAL GEOCHEMICAL PROBLEMS

Robert C. Harriss

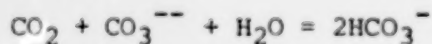
Many significant problems in geochemistry demand for their solution continuous and widespread measurements. Those of global concern involve the formulation of budgets for the elements or their compounds. Yet they become vexing due to inabilities up to the present to accumulate the data necessary for their consideration. Perhaps, inroads can be made using remote sensing techniques.

Foremost among these problems is the so-called "carbon cycle" which seeks a worldwide accounting of the compounds of carbon as well as those of calcium, strontium, magnesium, and other elements. The activities of human society are now altering the carbon cycle to such an extent that there may be serious implications for climate change and the consequential impacts upon living organisms. Two interrelated aspects of the carbon cycle may be amenable to solution with remote sensing techniques: the problem of carbon dioxide sinks and the areal extent of coral reefs.

The concentration of atmospheric carbon is increasing at a rate of about 1 percent per year from a preindustrial revolution value of 280 ppm. Today the value stands at 335 ppm. The increase is due to fossil fuel burning (coal, oil, and natural gas) and perhaps in part to the destruction of components of the terrestrial biosphere. Of the carbon dioxide introduced to the atmosphere from fossil fuel burning, it is estimated that about 50 percent has remained there; the rest is divided between the oceans (35 percent) and the terrestrial biosphere (15 percent) on the basis of model calculations.

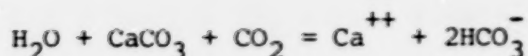
The possibility that the terrestrial biosphere is a source rather than a sink for atmospheric carbon dioxide has gained acceptance among many scientists. The practice of deforestation and the oxidation of soil organic matter may mobilize carbon dioxide in amounts similar to those resulting for fossil fuel burning. Thus, an additional demand may be placed upon the oceans to accept carbon dioxide.

The uptake process by marine surface waters, if equilibrium takes place, can be represented by the equation



The accommodation of carbon dioxide in the marine system would result in an increase in carbon dioxide and bicarbonate ion in surface waters, a decrease in carbonate ion, and no change in the carbonate alkalinity.

But such a reaction may be complexed by the interaction of the dissolved carbon dioxide with marine carbonates, namely,



If such a reaction takes place, there would be an increase in both carbonate alkalinity and in bicarbonate ion concentration.

For an assessment as to which, if either, of these two possibilities is important in the present day carbon cycle, we need to monitor globally the carbonate and bicarbonate concentrations in surface waters of the world ocean. Assuming equilibrium, a 10 percent increase in carbonate alkalinity would accompany a change of atmospheric carbon dioxide levels from 280 to 335 ppm, if dissolution of CaCO_3 takes place. Such measurements would also provide an estimate of the degree of calcium carbonate saturation in surface waters. These studies should be complemented with investigations of the downward mixing of the surface waters and might be carried out simultaneously on a remote sensing vehicle.

Another potential sink for atmospheric carbon dioxide is incorporation into the biosphere which may be enlarged from increased carbon dioxide levels. Recent investigations suggest that the amount of industrially produced carbon dioxide in sedimentary matter is comparable to the amount of combustion carbon as yet unaccounted for. Thus, it is important to monitor the freshwater and oceanic biomass and associated dissolved organic carbon.

The urgency to ascertain the extent to which surface waters of the world ocean can accommodate carbon dioxide from the atmosphere relates to a prediction that an average 2° to 3° C temperature rise, with an 8° rise in high latitudes, will take place by 2050 with a doubling of atmospheric carbon dioxide levels. There would be a shifting of the Earth's climatic regimes and some melting of the ice-caps.

Finally, an assessment of the depositional rates of calcium carbonate in coastal marine zones is warranted. Of great importance in the marine carbon budget are coral reefs. They appear to accommodate an amount of carbon annually that is equal to the amount delivered by the rivers to the world ocean. The coral reef formations are substantially involved in the geochemical mass balances of strontium, magnesium, and fluoride, as well as other elements. If their overall net growth today is negative, they can provide a way to bring more carbon dioxide into the ocean system. There is an urgent need for an inventory of coral reef areas and types and the associated oceanographic climatic conditions. Satellite imagery and air photography would be employed. Parallel inquiries to published papers, atlases, and hydrographic charts would provide essential surface truth.

The atmospheric burdens of many heavy metals are poorly understood and their sources may be identified by remote sensing techniques. The relative enrichments of such elements as copper, zinc, silver, and chromium in the atmosphere over their values in crustal rocks appear to be nearly uniform over the Earth's surface although the concentrations of a given element may vary markedly from place to place. The elements enriched in the atmosphere are those that are volatile themselves or have volatile compounds. Conventional wisdom indicates

that these metals have natural, as opposed to anthropogenic, sources. Origins for them might be vegetation, volcanos, crustal rocks, the sea surface, or man's activities. Some of these metals may jeopardize the well being of living organisms if exposure levels are high. Thus, the determination of the relative contributions of natural and anthropogenic inputs to the atmospheric burdens of these metals can provide regulatory agencies with a scientific basis to evaluate potential hazards. Such data may be of interest to epidemiologists who seek relationships between the geographic occurrences of disease and environmental factors.

The measurement of fluxes from the Earth's solid and liquid surfaces is an extremely difficult task. Still, the recent developments through remote sensing in the measurement of wind velocities may provide a simple entry to the problem. If both the wind velocity and the atmospheric burden of a metal in an air column can be simultaneously measured, a flux can be obtained. Needed researches into the atmospheric heavy metal problem might be initiated in the laboratory and extended in the field with the aim of measuring heavy metal fluxes from forested and vegetated areas, from volcanos, from different types of crustal rocks, from soils, and from sea surfaces. In addition, where possible, the species of the metal involved should be sought for a better understanding of the atmospheric behavior of the element.

In both the carbon cycle and heavy metal fluxes problem, it is recognized that present day technologies are not as yet developed for immediate applications. Yet, it appears that such techniques as laser induced fluorescence and Raman backscatter remote sensors may be capable of solving these problems.

IV. GAS AND AEROSOL FLUXES

Christopher S. Martens

A. Introduction

Atmospheric chemical processes are intimately linked to hydrospheric processes through the transfer of gases and aerosols. These transfers, or fluxes, are defined as the material transport per unit area per unit time. There is a growing realization that, through the addition of energy or materials, mankind has the capability to significantly alter the chemical composition of the atmosphere and the heat budget of the Earth (e.g., Kellogg, 1978). For example, increasing emissions of fluorocarbons for which the stratosphere appears to be the major sink, may lead to significant depletion of stratospheric ozone in the decades ahead (Singh et al., 1979).

Unfortunately we lack adequate data concerning global distributions and fluxes of both man-made and natural materials important in resolving these problems as well as understanding natural geochemical cycles. For example, the sources, sinks, and atmospheric lifetime of N_2O are not well understood (Liu et al., 1977). Its role in stratospheric ozone depletion as well as the nitrogen cycle therefore remains uncertain. Another example is the uncertainty in sea-salt aerosol production rates. Recent tropospheric budgets for materials such as arsenic (Walsh et al., 1979) include estimates of sea-salt production rates (e.g., Eriksson, 1959) which have high uncertainties.

The global scale need for accurate distribution and flux determinations for such materials represents a major problem area potentially amenable to applications of remote sensing technology.

In the following sections discussions of three priority problem areas are presented:

- (1) Trace gas fluxes;
- (2) Sea-salt aerosol production; and
- (3) Effect of sea surface microlayer on gas and aerosol fluxes.

Discussions of trace gas fluxes are emphasized because of their potentially key role in the stratospheric ozone depletion hypothesis. Secondary emphasis is placed on the latter two topics because of their significance in geochemical budgets and association with air-sea interface processes. Included in the trace gas section is a brief discussion of gas flux measurement methodology.

B. Trace Gas Fluxes

Volatile sulfur, carbon, nitrogen, and halocarbon compounds will be considered in this section. A statement of the problem associated with each compound or group of compounds, brief summary of our current understanding, and suggestions for needed research will be presented for each. The term "hydrosphere" is broadly defined to include waterlogged soils.

1. Gas Flux Measurements Techniques

Gas fluxes from soils have generally been measured with open-bottomed chambers which either seal off a volume of air over a known soil area (closed chamber) or are partially open to continual artificially induced or filtered air flow across the soil surface (open chamber; see Matthias et al., 1978, for review). Gas fluxes are deduced from concentration changes in closed chambers. Gas concentration differences between entering and leaving air or build-up in an in-line collection system can be utilized to determine fluxes in open chamber systems.

Open chamber methods similar to those currently in use appear to originate with the work of Pearson et al. (1965) who designed a recirculating, turbulently mixed chamber system for measuring soil radon-222 emanation. Their results suggested the importance of atmospheric turbulence in controlling flux rates, a result confirmed only for coarse soils by Kimball and Lemon (1971). Kanemasu et al. (1974) have since demonstrated a "suction" flux enhancement associated with open chamber measurements, while Matthias et al. (1978) have shown that less disturbance to natural soil gas concentration profiles results from their use.

Both closed and open chamber methods have been used in recent studies of sediment-water fluxes of the dissolved gases methane (King and Wiebe, 1978; Martens and Klump, 1980), and radon-222 (Hammond and Fuller, 1979; Martens et al., 1980).

Air-sea gas fluxes are usually indirectly calculated using the classical stagnant film model of Lewis and Whitman (1924) as described by Broecker and Peng (1974). In this model gas fluxes are assumed to be controlled by molecular diffusion across a thin stagnant film, the log of which has been shown to be linearly proportional to wind speed (Emerson, 1975).

Measurements of vertical gradients in wind speed and gas concentrations can also be utilized to calculate vertical gas fluxes through a horizontal plane using the equation (Lemon and Lemon, 1979):

$$F = \frac{k^2 (\mu_2 - \mu_1) (c_1 - c_2)}{\left(\ln \frac{z_2}{z_1} \right)^2}$$

where k is von Karman's coefficient, μ is wind speed, c is gas concentration, and z is height.

The methods above provide total flux measurements. Insufficient flux data are available for most gases from which to construct accurate global flux estimates. Consequently, such estimates have been made from interhemispheric tropospheric concentration differences for gases such as methane (Ehhalt, 1977) and CH_3Cl (Jesson et al., 1977; Singh et al., 1979). Assuming an inter-hemispheric exchange rate of 1 year (Czeplak and Junge, 1974), this technique

is useful for gases with residence times on the order of years. Lodge et al. (1974) have pointed out the lack of applicability of such flux calculations methods to short-lived gases such as H_2S and NH_3 .

2. Sulfur

Statement of problem

A major entry in current global sulfur budgets is an, as yet, unidentified flux from the Earth's surface to the atmosphere (Kellogg et al., 1972; Friend, 1973). The dominant site or sites of this flux as well as the most important chemical species involved are not presently known, although the sulfur is thought to be of biogenic origin (Lovelock et al., 1972; Rasmussen, 1974; Hitchcock, 1975; Graedel, 1977; Adams et al., 1979). It is important to address this problem because of the significance of both gaseous and particulate sulfur compounds in both urban and rural environments. In addition, other problems such as the possible importance of carbonyl sulfide (COS) in the formation of the stratospheric sulfate layer (Crutzen, 1976; Sze and Ko, 1979) need to be resolved.

Present understanding

Current global sulfur budgets are in reasonable agreement and suggest that a biogenic flux of approximately 150 ± 75 megatons of sulfur from land and ocean to the atmosphere is required for a balance cycle (Kellogg et al., 1972; Friend, 1973). Until the early 1970's it was generally thought that H_2S was the major biogenic sulfur contribution. Later studies by Lovelock et al. (1972) and Rasmussen (1974) suggested $(\text{CH}_3)_2\text{S}$ or CH_3SSCH_3 as being more important. Recent studies by Adams et al. (1979) suggest that a larger array of compounds should be considered including CS_2 and COS. The picture is further obscured by oxidation processes. Zinder et al. (1977) report that H_2S and CH_3SH (methyl mercaptan) are the major volatile sulfur compounds produced by algal mats under anaerobic conditions and that CH_3SSCH_3 emitted from such mats may be an oxidation product of CH_3SH . Sze and Ko (1979) have suggested that COS may be an oxidation product of CS_2 or $(\text{CH}_3)_2\text{S}$ although Graedel (1977) has suggested that SO followed by SO_2 is the most likely product.

Additional complications include physical and biological factors such as temperature dependency of fluxes and condition of biogenic emission sources. For example, Adams et al. (1979) have presented data suggesting that CS_2 is an important emission from injured salt marsh grass. Brinkman and Santos (1974) have suggested that the emission of H_2S from the Amazonian flood plain lakes coincides with the falling water period.

Needed research

A major gap is the lack of quantitative flux measurements for the variety of compounds discussed above. The behavior of the major S species in both the water column and atmosphere is poorly understood. Man's demonstrated impact on the global sulfur cycle (e.g., Kellogg et al., 1972; Berner, 1971) points to a need to locate the sites of fluxes to the atmosphere. When the site(s) and important species are identified, the impact of fluxes on a hemispheric to

local scale can be more readily assessed. Measurements of the fluxes of key chemical species across the range of environments from open ocean to coastal are needed.

3. Nitrogen

Statement of problem

The global nitrogen cycle begins with the fixation of atmospheric nitrogen. As an essential nutrient fixed nitrogen is assimilated by organisms, discharged through their subsequent decay or as waste, further recycled through oxidation-reduction reactions, and returned to the atmosphere following denitrification (Delwiche, 1970; Delwiche and Bryan, 1976). The rates of several of these processes are poorly known on a global scale at present. As man's production of N fertilizers increases the question of how the N cycle will adjust must be addressed. Active N compounds in the atmosphere (NO , NO_2 , HNO_3 , and NH_3) can exert control over gas-phase chemistry and precipitation pH, while N_2O is the source of stratospheric NO_x important in stratospheric ozone chemistry (Crutzen, 1970; 1979).

Present understanding

Reviews in articles by Delwiche (1970), Delwiche and Bryan (1976), and Liu et al. (1977) adequately outline our current understanding of the nitrogen cycle. The rapidly increased usage of industrially produced nitrogen fertilizers (≈ 6 percent per year) should result in increased N_2O production which, according to McElroy et al.'s (1976) predictions, could result in 20 percent reductions of ozone by the year 2025. Liu et al. (1977) have reduced this estimate to a 1 to 2 percent global ozone reduction in the next 50 years, but point out that the sources, sinks, and lifetime of N_2O are not well understood.

Man's production of fixed N is having an impact on coastal waters where N is often the limiting essential nutrient (Ryther and Dunstan, 1971).

Needed research

The results of Liu et al. (1977) and other more recent studies (R. Cicerone, personal communication, 1979) suggest that N_2O production may not offer as great a threat to the stratosphere ozone layer as some other compounds including volatile halocarbons (see below). However, the problem warrants continued study.

Quantification of the global nitrogen cycle will require better estimates of fluxes between the hydrosphere and atmosphere. Determination of oceanic nitrification and denitrification rates remains as a major problem. Other gaps in present understanding include mechanisms of microbially mediated chemical transformation processes in a range of environments from anoxic sediments to aerobic waters as well as surface microlayers. Transport mechanisms for the various gaseous (e.g., N_2 , N_2O) and aqueous (e.g., NO_3^- , NH_4^+) species between sedimentary, aqueous, and atmospheric environments must also be further elucidated.

4. Methane

Statement of problem

Tropospheric methane concentration data collected over the past decade (Ehhalt, 1977) appear to suggest a 10 to 15 percent rise. Such a rise would imply significant effects on atmospheric chemical and radiative effects. The sites and magnitudes of methane fluxes for terrestrial and marine methane reservoirs are yet to be delineated.

Present understanding

Calculations of a 10 to 15 percent rise in tropospheric methane concentrations based on an annual 1966-1967 average tropospheric concentration of 1.41 ppmv (Ehhalt and Heidt, 1973) and more recent data yielding concentrations above 1.5 ppmv (e.g., Swinnerton cited in Ehhalt, 1977) may be incorrect (R. Cicerone, personal communication, 1979). The 1966-1967 data appear to be systematically low due to calibration errors; however, there remains evidence for a less significant concentration increase.

Current estimates of the atmospheric lifetime of methane in the troposphere (Ehhalt, 1977; Singh et al., 1979) are based on the interhemispheric concentration difference and calculated production rates between hemispheres. Global methane production can be estimated as the total tropospheric methane concentration divided by the atmospheric lifetime. The production estimate of about 7×10^{14} g methane/yr obtained agrees well with the predicted $5.5 - 10.4 \times 10^{14}$ g/yr flux estimate based on extrapolations from various ecosystems (Ehhalt, 1974).

Needed research

The distribution of important flux sites is unknown and therefore a mechanism for any atmospheric increase cannot be identified. Because atmospheric methane concentration variations have important consequences for global atmospheric processes, an understanding of the coupling between production rates and human activities is needed.

5. Halocarbons

Statement of problem

Fluorocarbons and certain chlorocarbons such as methyl chloroform (CH_3CCl_3) have been identified as major potential depleters of stratospheric ozone (Singh et al., 1979, and references therein). Data of Singh et al. (1979) suggest an average annual increase of F-12 (CCl_2F_2) and F-11 (CCl_3F) of 10 and 12 percent, respectively. The implications of increases in these and other fluorocarbons and chlorocarbons are for depletion of stratospheric ozone.

Present understanding

Singh et al. (1979) present the first extensive global measurements of halocarbons which allow for accurate calculations of atmospheric residence times of halocarbons using interhemispheric tropospheric concentration differences and emissions data. Results for F-12 and F-11 suggest residence times of 65 to 70 and 40 to 45 years, respectively, ruling out the missing sinks suggested by Lovelock et al. (1973) on the basis of earlier data. F113 ($\text{CCl}_2\text{FCClF}_2$) and F114 ($\text{CClF}_2\text{CClF}_2$), also man-made and emitted primarily in the northern hemisphere, appear to have stratospheric sinks.

CH_3CCl_3 , with a tropospheric residence time of about 8 to 10 years (Singh et al., 1979), appears to be increasing at a rate of 17 percent annually in agreement with worldwide emission increases. An estimated 15 to 20 percent of the total should enter the stratosphere. Based on tropospheric and surface ocean concentrations the ocean is inferred to be a source of CH_3Cl .

Needed research

Further global data sets and studies of the tropospheric residence times and emissions of halocarbons are needed in order to assess the impact of man-made emissions on stratospheric ozone. The fluorocarbon compounds may be used as tracers for global circulation while more reactive compounds such as CH_3CCl_3 may be used for quantifying the role of the hydroxyl radical (HO) in cleansing the atmosphere (Singh et al., 1979).

C. Sea-Salt Aerosol Production

Statement of problem

It is believed that the major source of airborne sea-salt particles is bursting bubbles (Blanchard and Woodcock, 1957). The total production estimate of $1000 \times 10^{12} \text{g/yr}$ (Eriksson, 1959) used in current tropospheric budget calculations (e.g., Walsh et al., 1979) is based on estimated removal rates which are assumed to equal the production rate. It is also assumed that precipitation removal is equal to calculated dry fallout over the sea. We need more accurate estimates of sea-salt particle production.

Present understanding

Eriksson's (1959) calculated production rates are still in use. Quantitative data concerning the concentration of sea-salt aerosol in various ocean regions is becoming available (e.g., Lovett, 1978). Correlations between airborne sea-salt concentrations and wind speed (Woodcock, 1953; Blanchard and Syzdek, 1972; Lovett, 1978) are in good agreement and aerosol residence times on the order of 12 to 25 hours have been calculated.

Needed research

It should be possible, with adequate global wind speed data and/or direct aerosol concentration determinations, to improve estimates of total airborne

sea-salt inventories. The combination of better inventory and mean residence times could yield improved sea-salt aerosol production estimates.

D. Sea Surface Microlayer Problem

Statement of problem

Sea surface microlayers, surface films, or "slicks" are known to play a role in gas and aerosol exchange between the hydrosphere and atmosphere (see MacIntyre, 1974, and Liss, 1975, for reviews). Recently the role of microlayers in horizontal chemical transport of materials in estuaries has been elucidated (Pellenbarg and Church, 1979). We know little about the overall geochemical significance of surface microlayers because of restricted sampling capabilities.

Present understanding

Sea surface microlayers, surface films, or "slicks" are known to influence wind speeds near the air-sea interface (Barger et al., 1970), sea-salt particle production (Garrett, 1968; Paterson and Spillane, 1969), and chemical transport processes (e.g., MacIntyre, 1974; Liss, 1975; Pellenbarg and Church, 1979). Thickness of the microlayer is thought to be 100 μm or less (Liss, 1975). The enrichment of organic materials, certain metals, and other compounds in microlayers (e.g., Piotrowicz et al., 1972) may account for differential chemical transport between the hydrosphere and troposphere. Horizontal chemical transport by surface microlayers has also been shown to be important in salt marsh trace metal cycling (Pellenbarg and Church, 1979). Current sampling techniques include stainless steel or plastic mesh, which remove the upper 300 μm , drum "skimmers" which roll over the surface picking up the upper 60 to 100 μm , bubble microtomes, and glass plates or slides which pick up surface films when dipped vertically (see Liss, 1975). The mesh and drum samplers sample 100 \pm 50 μm thick samples whereas the bubble microtome and slide methods sample much thinner layers. None of the techniques are well suited for large-scale studies of surface microlayer distribution especially under poor weather conditions.

Needed research

The development of remote sensing techniques addressing almost any aspect of the surface microlayer problem would help to open the way for improved understanding of their overall significance and role in geochemical processes.

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V. COASTAL SEDIMENTATION

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A. Introduction

In this section several important coastal sedimentation problems are identified where application of existing or anticipated remote sensing technology might provide valuable information.

B. Coastal Fine Particle Sediment Systems

Particles are added to the coastal marine environment by rivers, the atmosphere, shore erosion, biological activity, and by municipal and industrial discharges. The particles are both organic, living and dead; and inorganic, naturally occurring and anthropogenic. Man has clearly modified the flow of natural particles into coastal systems by land-use practices--deforestation, agriculture, urbanization--and by water-use practices--construction of dams and reservoirs, diversion of rivers and streams, construction of shore protection devices, etc. His activities have also introduced significant quantities of anthropogenic particulate matter.

Because particulate matter can strongly affect the quality of the coastal environment in a variety of ways, the ability to predict its behavior is of the greatest scientific and practical importance. This is particularly true of the fine-grained fraction which poses the greatest problems: economic, aesthetic, and environmental.

The ultimate objective is to understand how fine-grained sediment systems of coastal waters operate. Among the most important questions are:

- (1) What are the sources of sediment, their locations and strengths?
- (2) What is the character of the material introduced, its size distribution, composition, and associated contaminants?
- (3) What are the routes and rates of sediment transport?
- (4) What are the sites of accumulation, the transient repositories, and the final resting places?
- (5) What are the rates of accumulation in these repositories and how much material is lost to the ocean?

There is not a single coastal system for which all of these questions can be answered satisfactorily for scientific or management purposes. Coastal systems are heterogeneous (patchy) in many of their characteristic properties and sediment sources vary markedly temporally. Adequate characterization with conventional shipboard techniques would require many samples collected nearly synoptically, and observations over long periods of time. With present sampling techniques, such sampling programs are not practical. Remote sensing from

satellites, and particularly from aircraft, may provide valuable tools for studying coastal sediment systems, but before they can be usefully employed, certain questions must be answered. Some of the most important questions are listed below.

- (1) Can remote sensing techniques distinguish suspended organic particles from inorganic particles?
- (2) Can remote sensing techniques be used to estimate the concentration of total suspended solids? Over what range in concentrations?
- (3) Can remote sensing techniques integrate over the water column to estimate the total suspended load? To what depth and over what range of concentrations?
- (4) Can remote sensing techniques be used to estimate the partitioning, by sedimentation, of suspended solids among different segments of an estuary or other coastal embayment?
- (5) What sea-truth measurements are required for calibration of remote sensing observations?

Concentrations of total suspended matter in coastal areas range from less than 1 mg/l to many thousands of mg/l, and even into the hundreds of thousands of mg/l off the mouths of some large rivers such as the Yellow and Yangtze. Over the length of an estuary the total concentration may drop by one to two orders of magnitude between the head and the mouth and the partitioning of mass between the inorganic and organic fractions may change from >99:1 at the head to <1:99 at the mouth. The size distribution may also change significantly over the length of an estuary. And large variations are not confined to changes over relatively large distances in the horizontal; large changes may occur over relatively small distances in the vertical. For example, in the upper reaches of the Chesapeake Bay estuary the concentration of total suspended matter may increase by at least a factor of 20 over a depth of <5 m between the surface and near the bottom.

Temporal variations in the concentration of total suspended matter can also be very large. Seasonal variations of the concentration of total suspended matter of one to two orders of magnitude are relatively common in temperate estuaries, and episodes can increase concentrations substantially above normally high values. Variations of higher frequency are also common. Near-bottom concentrations may vary by several orders of magnitude over periods of hours as bottom sediments are resuspended by wind waves or tidal scour. In the Chesapeake Bay, Schubel (1971) found variations in the concentration of total suspended solids of semitidal period of >20X with concomitant changes in the mean diameter of the suspended particles of from about 2 μ m near times of slack water when concentrations were low to more than 20 μ m near times of maximum ebb and flood tidal currents when concentrations were high.

C. Events and Coastal Sediment Systems

Recent studies have shown that events such as floods and hurricanes can dominate the sedimentation of coastal systems (Chesapeake Research Consortium, 1976). Schubel (1974) showed that during Tropical Storm Agnes (June 1972), the Susquehanna River - the principal source of fluvial sediment to the Chesapeake Bay - discharged more suspended sediment in 1 week than it does during 25 years of average runoff. Hirschberg and Schubel (in press) showed that two floods, Agnes in 1972 and the Great Flood of 1936, accounted for more than one-half of all sediment deposited in the upper Chesapeake Bay since 1900. Other investigators have shown that inlets cut during hurricanes can completely alter the circulation and sedimentation of bar-built estuaries and lagoons. It is clear that while they have a low frequency of occurrence, episodic events can dominate the natural evolution of coastal water bodies.

Synoptic observations are desirable during events because water properties frequently change rapidly in time and space during and immediately following events. Shipboard observations during this period are, at best, difficult to make because of weather and sea conditions and synoptic observations over relatively large areas are virtually impossible. While cloud cover may frequently rule out satellite observation during episodic weather events, low flying aircraft might be useful. Because of their very nature, episodic events frequently cannot be predicted very far in advance, if at all. The key to effective studies is rapid response. Aircraft that could be deployed quickly with remote sensing packages could provide very valuable data for science and management.

Among the more important geological questions relating to episodes are:

- (1) During floods how much sediment is discharged to the coastal zone?
- (2) Where are the principal sources of this material - upland areas, bank erosion, purging of reservoirs, etc.?
- (3) What is the ultimate fate of the material? How is it partitioned among different segments of an estuary or other coastal embayment?
- (4) How rapidly does the system recover to normal levels of total suspended solids?
- (5) What changes in shoreline configuration are produced - erosion, deposition, formation of new islands, cutting of new inlets, etc.? Does the system recover, and over what time scales?
- (6) How much sediment is discharged to the ocean and what is its fate?
- (7) What is the importance of episodes, relative to average conditions, in determining the natural geological evolution of coastal systems?

Remote sensing techniques, particularly from low flying aircraft, should be very useful in answering a number of these questions. Sea-truth data will certainly be required, not only for calibration of the remote sensing data but to extend the observations to greater depth. Concentrations of total suspended solids may be so high (>1000 mg/l) that penetration of optical signals will be limited to a thin near-surface layer.

A series of approximately daily over-flights would be desirable throughout the recovery period.

D. Routes and Rates of Sediment Transport on Continental Shelves

Relatively little is known about the routes and rates of sediment transport on the continental shelves of the world. This is particularly true of the fine-grained fraction, the silt and clay-sized particles. Aside from the obvious scientific reasons for wanting to understand the dispersal of sediments on continental shelves, there are important practical reasons. With the increasing potential for use of our continental shelves for energy-related activities - for oil exploitation and siting of floating nuclear power plants - and with increasing exploitation of sand and gravel resources, it will become increasingly important to be able to predict the routes and rates of sediment transport. Fine particles are the principal pathway for carrying particle-associated contaminants (e.g., oil, radionuclides, and metals) in continental shelf waters back to the continents and therefore to man. The mobility of the bottom must be considered in the siting of facilities, laying of pipelines, etc.

With present shipboard techniques, it is impossible to obtain a synoptic view of a relatively large segment of the continental shelf. This information is particularly important for studies of fine-particle systems. An assessment of the mobility of the bottom - movement of bedforms - with present shipboard techniques is equally intractable. Remote-sensing from satellites and aircraft may provide useful data for answering both of these sets of questions.

Some of the more important questions include:

- (1) What are the distributions of total suspended matter in time and space?
- (2) What are the sources of sediment to continental shelves?
- (3) What are the routes and rates of transport of fine-grained sediments?
Do fine-grained particles constitute an effective mechanism for returning particle-associated contaminants back to land and to man?
Are fine-grained materials bypassing the shelf? If so, where are they being deposited and at what rates?
- (4) What are the routes and rates of transport of coarse-grained (bottom) sediments? What are the characteristic bedforms, how stable are they in time and space?

E. Dredging and Dredged Material Disposal

Since most of the nation's seaports are located on estuaries and since most estuaries are characterized by relatively rapid sedimentation rates, dredging has been a persistent activity of coastal areas since colonial days. The dredging has been a combination of new work and maintenance dredging. The development of facilities to support recreational boating and fishing and commercial fishing has also increased dredging activities. Throughout the U.S. more than 400×10^6 yd³ of material are dredged annually by the U.S. Army Corps of Engineers and over the past decade, an additional 75×10^6 yd³ have been dredged each year by nonfederally financed projects (Boyd et al., 1972).

Most dredged materials are composed of natural sediments eroded from upland areas and carried into coastal waters by rivers and streams. Other sources include shore erosion, primary productivity, and municipal and industrial discharges. The relative strengths of these sources vary with location and with time at any given location. The shoaling of channels is frequently dominated by a proximate source of sediment - the resuspension of bottom sediments by tidal scour and wind waves and the transfer of these materials into the channels where they are trapped. Since most of the materials that are dredged are natural soils and organic matter, one would expect that their disposal need not create any serious environmental problems. In general this is true. But pollutants are added to rivers and directly to estuaries and other coastal embayments by municipal and industrial discharges, and by accidental releases.

The sources of most pollutants are concentrated near cities and ports. Since many contaminants are relatively insoluble and have a high affinity for fine-grained particles, they are rapidly scavenged by fine suspended particulate matter and end up on the bottoms of estuaries and other coastal embayments where fine-grained sediments are accumulating. The disposal of these materials in open waters - the most common mode of disposal - has created a number of environmental problems, real and perceived. Several important questions related to the physics of disposal are listed below.

- (1) How extensive and persistent are plumes of suspended solids produced during open water disposal operations? What are the excess concentrations of suspended solids?
- (2) How stable are open-water deposits of fine-grained dredged materials? Are they confined to the disposal sites or are they resuspended by waves and currents and dispersed? If they are dispersed, what are the areas affected?
- (3) How can suitable potential open-water disposal sites be identified? Both "confinement" sites - natural sites from which materials will not be dispersed - and dispersal sites may be desirable.

While the first question is tractable with shipboard measurements, observations from aircraft could be useful, particularly during periods of rough seas, and to provide graphical synoptic coverage. The other two questions may be amenable to remote sensing. Determination of the stability of dredged material deposits is difficult with conventional shipboard sampling. It is frequently difficult to sample during periods of rough seas when dispersal is most likely to occur and areal coverage is frequently not adequate for management purposes. In relatively clear and shallow waters, remote sensing may be valuable in delineating changes in the areal extent of deposits of dredged materials if these materials are substantially different from the natural substrate.

There is a need to identify suitable open-water disposal sites for relatively uncontaminated fine-grained dredged materials, sediments that pass the present bioassay tests. Both confinement and dispersal sites are needed. Open-water confinement sites are those from which, because of natural processes, disposed materials will not be dispersed. Dispersal sites, on the other hand, are characterized by vigorous reworking by waves and currents and from which sediments will be broadly disseminated. In relatively clear and shallow coastal waters, remote sensing may be useful in identifying potential disposal sites. Changes in bathymetry, bed form movement, and near-bottom turbidity are indications of bottom stability.

F. References

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APPENDIX

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16. Abstract This document presents an assessment by a working group of the results of a workshop on "Remote Sensing and Problems of the Hydrosphere" (NASA Conference Publication 2109) and identifies those important problems whose solutions are deemed possible, especially as aided by remote sensing. This working group met in New Orleans, Louisiana, on May 9-11, 1979, and was sponsored by the NASA Office of Space and Terrestrial Applications and the Environmental Quality Projects Office of the NASA Langley Research Center. The scientific participants addressed these topics: Bioprocesses, Global Geochemical Problems, Gas and Aerosol Fluxes, and Coastal Sedimentation.					
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